Research of Earthquake Resistant Ductile Iron Pipe (ERDIP) for fault crossing

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Abstract

This study proposes a method for designing a water pipeline system against fault displacements by using Earthquake Resistant Ductile Iron Pipe (ERDIP). An ERDIP pipeline is capable of absorbing the large ground displacements that occur during severe earthquakes by movement of its joints (expansion, contraction, and deflection). Existing ERDIP pipelines have been exposed to several severe earthquakes such as the 1995 Kobe Earthquake and the 2011 Great East Japan Earthquake, and there has been no documentation of their failure in the last 40 years.

In the case of a pipeline that crosses a fault, there is the possibility of the occurrence of a local relative displacement of several meters between the pipeline and the ground. Hence, the present study was targeted at developing a method for designing an ERDIP pipeline that is capable of withstanding a strike-slip fault. This was done by FEM analysis, wherein 1500-mm shell elements were used to model the ERDIPs and spring elements were used to model the soil and ERDIP joints. An ERDIP pipeline can accommodate a fault displacement of about 2 m and the use of a “large displacement absorption unit” is an effective countermeasure for displacements exceeding 2 m.

INTRODUCTION

The 1995 Kobe Earthquake, which occurred just beneath the city, was caused by the movement of an active fault. In Awaji-shima Island, the movement of Nojima-fault affected the ground surface and it caused substantial damages to a lot of buildings [1], [2].

It has also been reported that the 1999 Chichi Earthquake in Taiwan and the 1999 Kocaeli Earthquake in Turkey induced surface fault displacements that damaged buried pipelines. The damages included compression and lateral deformations. Indeed, there have been instances when pipelines had to be installed across known faults and this required the design of the pipelines to absorb surface fault displacements.

An earthquake resistant ductile iron pipe (ERDIP) is capable of absorbing ground displacement in the event of an earthquake. This is achieved through a joint expansion/contraction and deflection mechanism. Over the past 40 years, ERDIP pipelines have been exposed to several earthquakes with seismic intensities of above 6, as well as accompanying severe liquefaction, such as occurred in the 1995 Kobe Earthquake and the 2011 Great East Japan Earthquake. Despite this, there has been no documented failure of an ERDIP pipeline. The earthquake resistance of ERDIP pipelines has been confirmed through observation of the pipe movement, joint movement, and pipe stress during earthquakes, as well as by liquefaction tests and post-earthquake surveys.

However, few studies have considered pipe movement and safety at fault crossings, and those that have were limited to small pipelines. In the present study, we focused on large-diameter pipes such as those of water systems, which could be damaged by an earthquake. We quantitatively measured the amount of fault displacement that a normal pipeline of such diameter could absorb and investigated countermeasures against large displacements.

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ANALYSIS OF PIPELINE BEHAVIOR AT FAULT CROSSING

Structure of ERDIP and its behavior

Fig.1 shows the joint behavior of a US-type joint, a type of an ERDIP joint, the performance of which was investigated in the present study. Table 1 gives the performance parameters of the joint. The joint is capable of expanding/contracting by 0.5% of its standard pipe length (e.g., 4 m in the case of DN1500). When the joint is fully expanded, the spigot projection and lock ring lock tightly together to prevent leakage resulting from pull-out of the joint.

Fig.2 shows the pipeline behavior during ground crack and subsidence. When a pipe joint is fully expanded or deflected, it may pull on other pipe joints one after the other to absorb the ground deformation. The pipeline is thus referred to as a “chain structure pipeline”. Buried ERDIP joints are not expanded by water pressure because the pipes are supported by the ground.

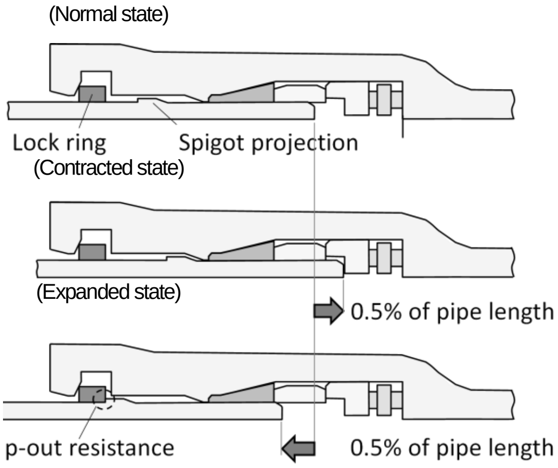


FIG.1 Joint behavior of US-Type joint

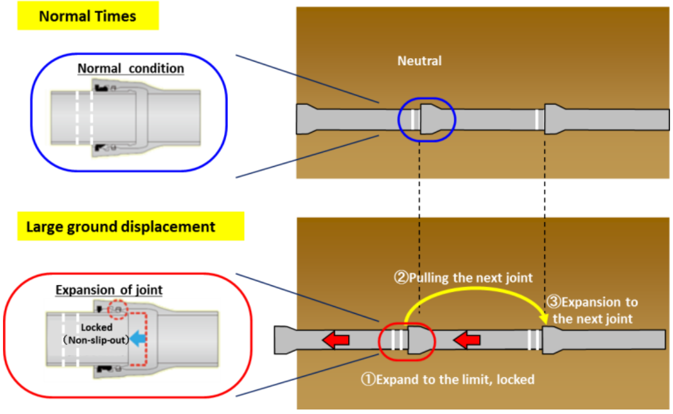


FIG.2 ERDIP pipeline behavior

Table.1 Joint behavior of US-Type joint

Property	Performance
Pull out resistance	3DkN（D：nominal daimeter mm）
Amount of expansion/contraction	±0.5% of pipe length
Deflection angle	4°(DN1500)

Table 2 Major fault in Los Angeles, US

Fault name	Slip rate (mm/year)	Average slip (m)
Newport Inglewood	1.5	1.7
Palos Verdes	3.0	2.8
Raymond	1.5	1.7
San Fernando	5.0	1.8
Santa Susana	5.0	2.1
Sierra Madre	2.0	3.3

Outline of fault model

Institute of Earthquake and Volcano Geology, a research institute of National Institute of Advanced Industrial Science and Technology (AIST), releases active fault database of Japan since 2005. As of Jan. 20, 2015, 389 cases are registered with fault displacement. Reverse fault is about 50% of all faults and 90% of inclination angles of these faults are 45°, 60° and 90°. Fig.3 shows distribution of displacement at active faults in Japan. According to this data, about 50% of active faults were displaced 2m or less. And about 75% of active faults were displaced 3m or less. In addition, Table 2 shows that the displacements of major faults in Los Angeles are mostly 3m or less.

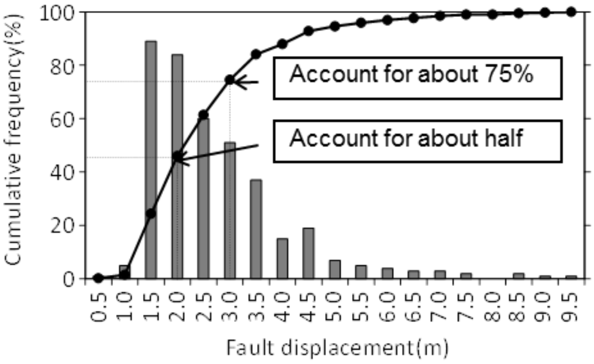


FIG.3 Fault displacement in Japan

Therefore, we set the upper limit of vertical fault displacement as 3m on this analysis model.

Analysis model

The analysis conditions are shown in Fig.4 and Table 3.

The pipeline model adopts DN1500 US-Type ERDIP which doesn’t include the fittings such as bends and Tees. The location of fault displacement is set so that the fault plane crosses the joint. The target range of analysis is 200m pipeline in order not to affect the fault movement to both ends. The length of each pipe section is 4m which is standard length of DN1500 US type ERDIP.

Fig.5 shows outline of analysis model. The ductile iron pipes are modeled by 3-dimension shell element. The charac- teristic of joint and soil are modeled by joint spring and soil spring respectively. Geometric non-linearity and also material non-linearity to evaluate the large pipeline displacement are the considered in the FEM analysis. (Software: Marc. Mentat)

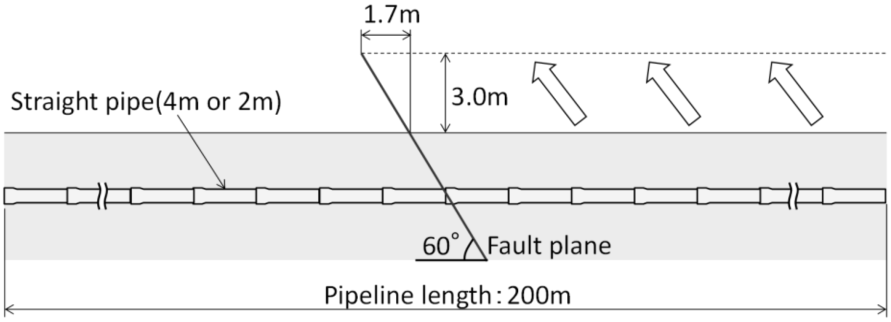


FIG.4 Analysis condition

Table.3 Analysis condition

Joint type	DN1500 US-Type joint
Pipe length	4m
Pipeline lengrh	200m
Amount of expansion/contraction	±0.5% of pipe length
Fault type	Strike-slip fault
Fault deflection angle	60°
Fault displacement	Orthogonal: 3m ,Axis: 1.7m
Coefficient of subgrade reaction	33,827 kN/m3

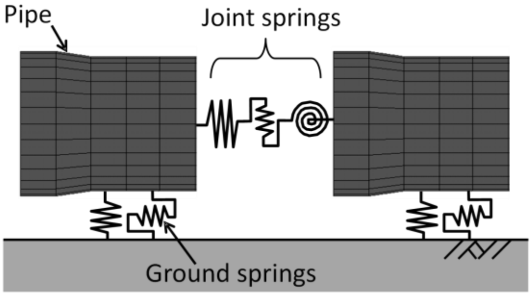


FIG.5 Outline of analysis model

Analysis condition

Criteria for evaluation. Table 4 shows the criteria for the evaluation. The stress generated on pipe body should be less than proof stress and the joint deflection angle should be equal or less than 4 degrees to keep the leak tightness performance. The axial force applied to the joint should be equal to or less than 3DkN (D: nominal diameter in millimeter)

Table.4 Criteria for evaluation

Joint		Pipe body
Axial force (kN)	Deflection angle (deg)	Stress (MPa)
4,500	4.0	270

Joint spring. The joint springs are defined based on the result of actual testing. Fig.6 shows the example of testing to determine the rotation spring of joint. Fig.7 shows the summary of joint spring. The axial direction spring has binary regions. In the 1st region (displacement 0 to δa), the joint can slide with small force because the resistance force is only friction between the pipe and rubber gasket. In the 2nd region (displacement over δa), the locking system of the joint can be activated, and the joint can’t slide any more.

The rotation spring also has binary regions. In the 1st region, the joint can deflect with small moment because the spigot cannot touch the socket inside. In the 2nd region, the resistance of rotation will be increased due to contact between the spigot and socket inside. The maximum deflection angle of DN1500 US-Type joint is 4 degrees.

Fig.8 shows the joint spring for shell element. They are set between each socket and spigot node with 3 directions (axial, normal and tangential direction) to coincide the characteristics of joint spring as shown in Fig.7. Fig.9 shows the comparison of joint rotation characteristic between the test result and joint spring. The joint spring is well accorded with test result.

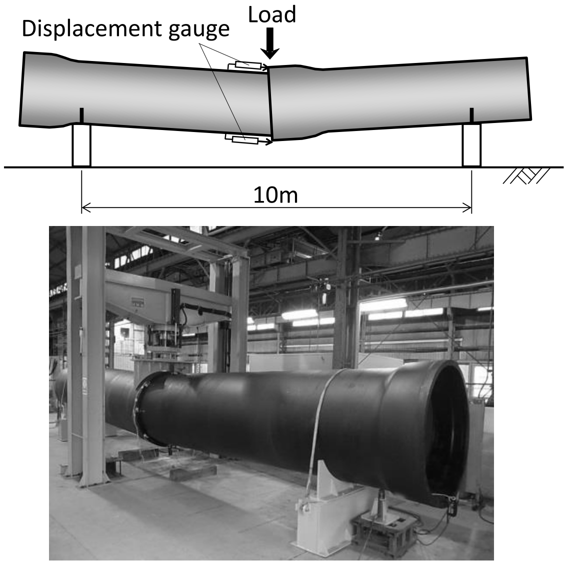


FIG.6 Test method to define rotation spring

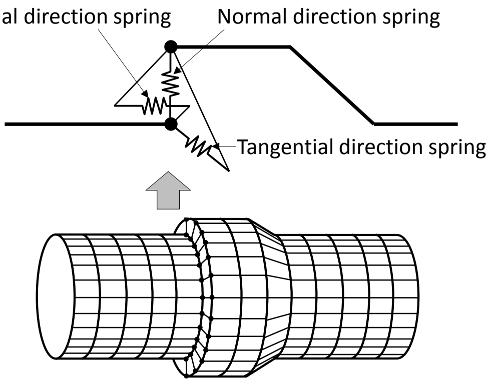


FIG.8 Joint spring for shell element

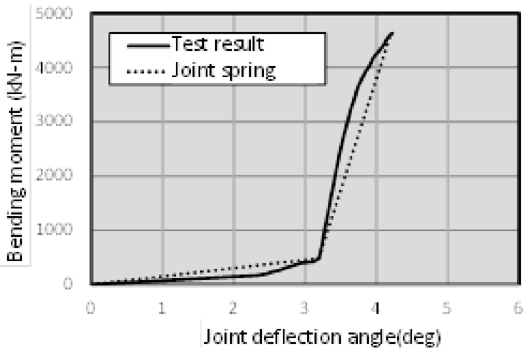
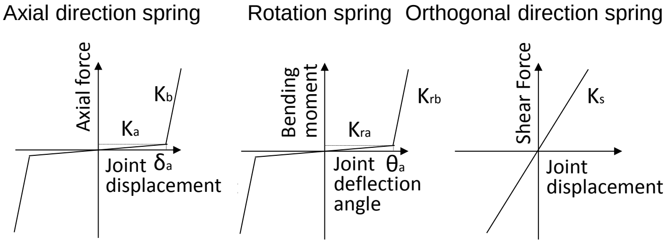


FIG.9 Comparison of joint rotation characteristic



Axial direction spring		Rotation spring		Orthogonal direction spring	
Ka	9.20×10^3(kN/m)	Kra	1.66×10^2(kN-m/deg)	Ks	2.0×10^6(kN/m)
Kb	1.98×10^6(kN/m)	Krb	4.28×10^2(kN-m/deg)		
δa	±0.0475(m)	θa	3.2(deg)		

FIG.7 Joint springs

Soil spring. Soil spring for axial direction is set as shown in formula (1a) based on previous study (See. Reference [14]). Internal friction angle of soil (Δ) is set 36 degrees based on the text (See. Reference [15]). In addition, soil spring is defined bi-linear model as shown in Fig.10 to be considered slip between the pipe and soil. Soil spring for orthogonal direction is set as shown in formula (2a) based on subgrade reaction modulus. In this study, soil springs are defined as general stiffness soil except to sufficiently high stiffness.

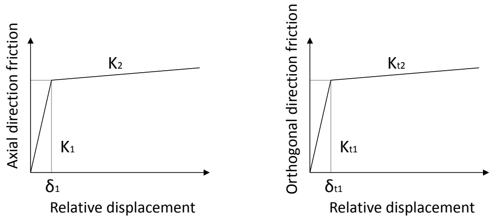
$$k_1 = \frac{\pi}{2} \cdot D \cdot \gamma \cdot \left(h + \frac{D}{2} \right) \cdot \left(1 + k_0 \right) \tan\Delta \cdot \frac{\ell}{\delta_1} \tag{1a}$$

$$k_2 = 0.001 \cdot k_1 \tag{1b}$$

$$k_{t1} = K \cdot D \cdot \ell \tag{2a}$$

$$k_{t2} = 0.005 \cdot k_{t1} \tag{2b}$$

k1, k2	Constant of axial direction soil spring
kt1, kt2	Constant of orthogonal direction soil spring
D	Outside diameter of pipe
γ	Unit weight of soil (=16kN/m3)
h	Depth of earth cover (=3.0m)
k0	Coefficient of lateral soil pressure at rest(=1.0)
Δ	Internal friction angle of soil (=36°)
$\delta 1$	Inflection point of axial direction spring
K	Subgrade reaction modulus
ℓ	Unit length of pipe



Axial direction spring		Orthogonal direction spring	
K_1	3.66×10^4(kN/m)	K_{t1}	5.26×10^4(kN/m)
K_2	$0.001\times K_{g11}$(kN/m)	K_{t2}	$0.005\times K_{g21}$(kN/m)
δ_1	0.0005(m)	δ_{t1}	0.0005(m)

FIG.10 Soil spring

Results of analysis

Fig.11 to Fig.15 show the example of analysis results. Horizontal axis of each figure is axial distance. The positon of fault displacement is defined as 0m.

The ERDIP pipeline can deform in accordance with fault movement as shown in Fig.11. The portion of pipeline located near fault deform largely more than the fault displacement to orthogonal direction (bending outside).

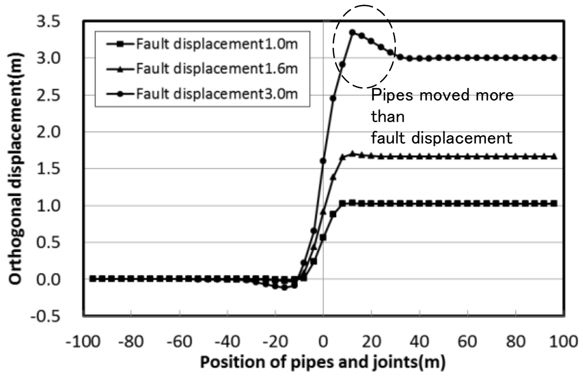


FIG.11 Pipeline displacement (Orthogonal direction)

Fig.12 shows the analysis results of joint deflection angle. The plus and minus mean the direction of joint deflection. In case of 3m fault displacement, 4 joints located near fault are deflected more than limit an gle (4 degrees).

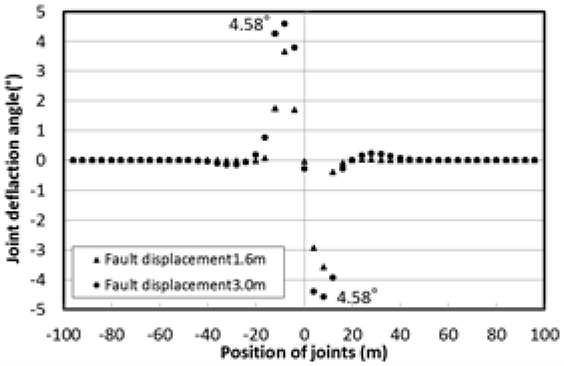


FIG.12 Joint deflection angle

Fig.13 shows the analysis results of axial force occurred at the joint. The plus and minus mean the expansion (+) and contraction (-) respectively. The maximum axial (contraction) force is generated at the joint located at the fault displacement. When the fault displacement is over 1.6m, the axial force exceeds 3DkN, which is performance limit of the joint. In case of 3m fault displacement, lots of joints exceed the 3DkN. This is because the total soil friction force generated on 140m of piping is acting on the joints near the fault location.

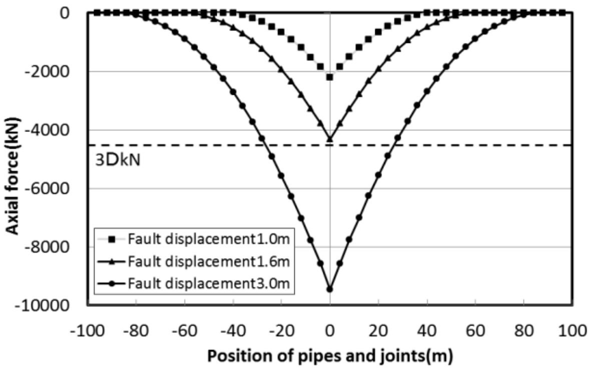


FIG.13 Axial force

Fig.15 shows the contour drawing of stress distribution generated in pipe body in case of 3m fault displacement. The stress generated in the portion of pipeline located 8m away from fault displacement is maximum stress, it is only 111MPa which is within elastic range.

The analysis results with respect to fault displacement are shown in Table 5. The ERDIP pipeline can withstand up to 1.6m fault displacement with its performance defined in Table 4. However, when the fault displacement exceeds 1.6m, axial force generated at joint is beyond performance limit (3DkN). Furthermore, in case of 3m fault displacement, not only axial force but also joint deflection angles exceed performance limit.

Table 5 Analysis results

Fault displacement (m)	Axial force (kN)	Stress (MPa)	Joint deflection (deg)
1.0	2,212	25	31
1.6	4,314	49	3.7
2.0	5,760	67	4.0
3.0	9,460	111	4.6
Allowance limit	4,500	270	4.0

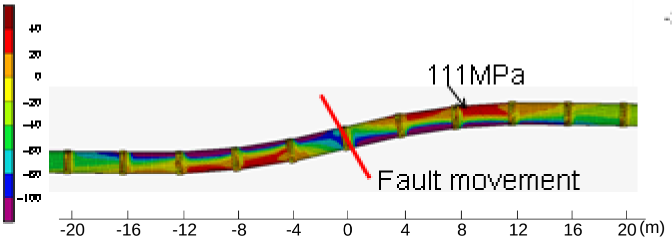


FIG.15 Stress distribution

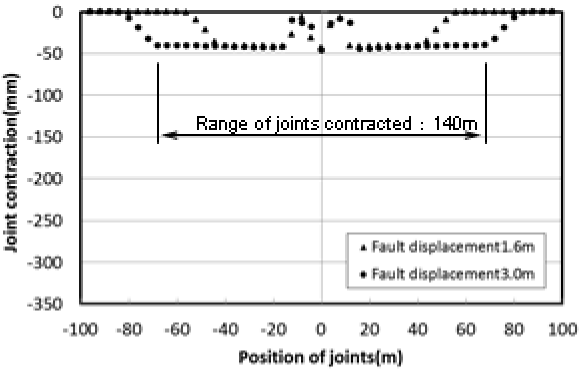


FIG.14 Joint contraction

ERDIP PIPELINE SYSTEM WITH 1.6M OR MORE FAULT DISPLACEMENT

Large displacement absorption pipeline system (LDAPS)

According to FEM analysis results in case of 1.6m or more fault displacement, the axial force generated at joints should be reduced because the axial force will reach 4,500kN which is the limit value of the joint. Also, the joints near the fault are subject to exceed the limit deflection angle due to the big axial force.

Therefore, we devise the large displacement absorption pipeline system (LDAPS) as shown in Fig.16.

The LDAPS is ERDIP with large displacement absorption units (hereinafter, unit) as shown in Fig.17.

The unit consists of long collar and ERDIP socket and spigot. The long collar has 10 times bigger expansion/ contraction amount (e.g. in case of DN1500, 600mm) and each ERDIP socket and spigot can deflect so that the unit can absorb locally-large relative displacement between ground and pipeline efficiently.

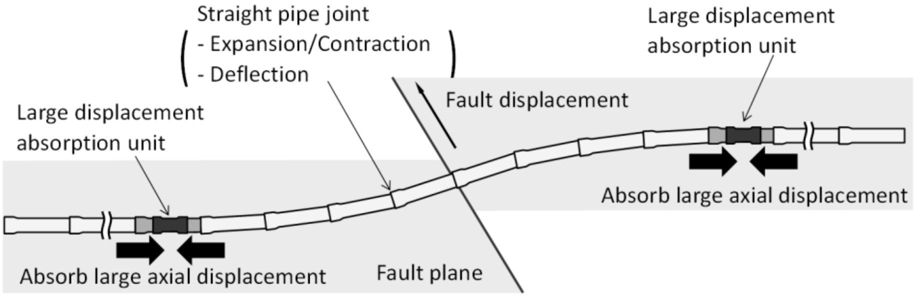
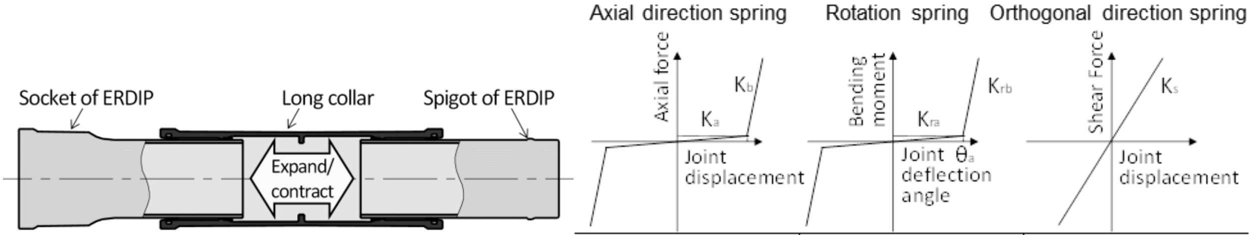


FIG.16 Large displacement absorption unit



Axial direction spring		Rotation spring		Orthogonal direction spring	
K_a	9.20×10^{3}(kN/m)	K_{ra}	1.66×10^{2}(kN-m/deg)	K_s	2.0×10^{6}(kN/m)
K_b	1.98×10^{6}(kN/m)	K_{rb}	4.28×10^{2}(kN-m/deg)		
δ_a	-0.3(m)	θ_a	0.5(deg)		

FIG.17 Large displacement absorption unit

The length of unit will be equal or less than pipe length so that the deflection performance of unit has equal to or more than pipe joint. Since there are no specialized pipes, the pipeline design and installation will be easy. The units should be placed where the joints are not subject to deflection angle of less than 1 degree. The span of each unit can be calculated as 36m (See Fig.18).

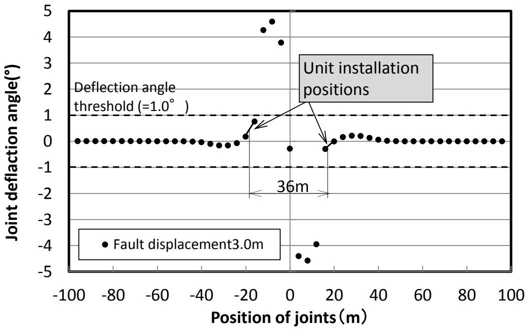


FIG.18 Unit installation

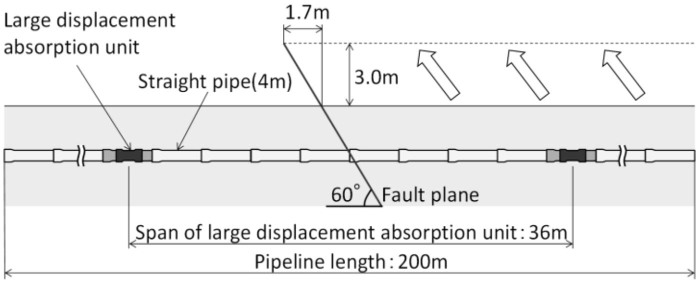


FIG.19 Analysis condition

Analysis results of LDAPS

To verify the effectiveness of LDAPS, we conduct FEM analysis. The analysis conditions are same as straight pipeline case (Table 3). The length of LDAPS is 200m. The units are placed at 36m intervals. The fault displacement is located in the center. Fig.19 shows analysis condition for LDAPS.

The results of analysis are shown in Fig.20 to Fig.24. White plots in the drawing stand for the joint of long collar.

As shown in Fig.20, the range of joints contracted is reduced up to 72m.This is because the units absorb locally-large axial displacement. In consequence, the axial force can be dramatically reduced compared to regular ERDIP pipeline due to the reduction of friction force from the ground as shown in Fig.21. It was found that the span of units is important factor for the reduction of axial force. Because the axial forces are dramatically changed at the unit portion and increased from units toward fault movement.

Fig.22 shows the pipeline displacement. The pipeline displacement at the portion of “A” toward bending outside direction can be reduced due to the reduction of the axial f orce. In consequence, the joint deflection angle can be reduced less than performance limit (4 degrees).

Fig.24 shows the stress distribution on pipe body. The stress is totally-smaller than in case of regular ERDIP pipeline (Fig.15).

According to above results, it was found that LDAPS can be used for 3m displacement fault crossing pipeline as the pipeline stress keep within elastic range. Furthermore, the LDAPS is effective

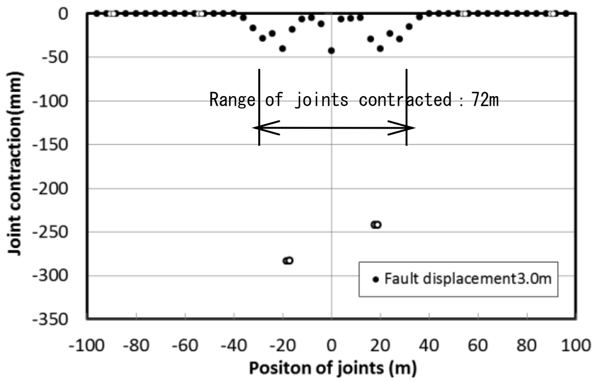


FIG.20 Joint contraction

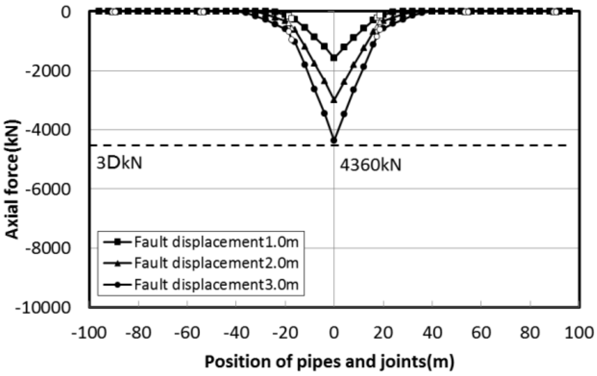


FIG.21 Axial force

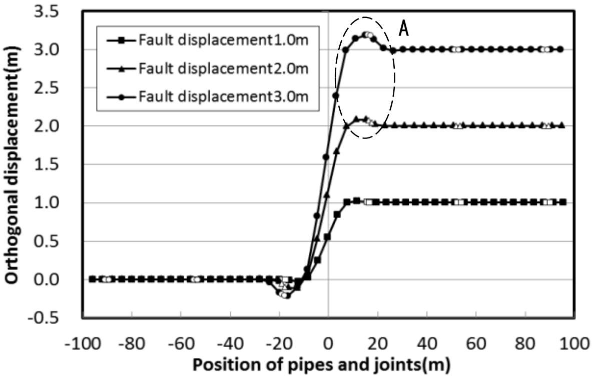


FIG.22 Pipeline displacement (orthogonal direction)

design method against larger fault displacement because the LDAPS can improve the performance with the number of unit and span of unit in accordance with fault displacement.

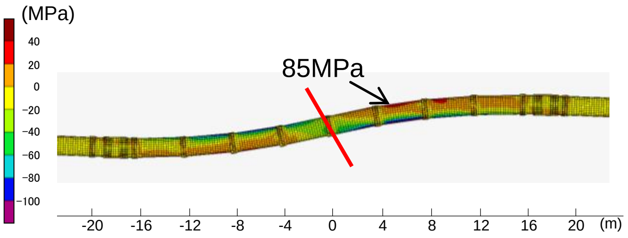


FIG.24 Stress distribution

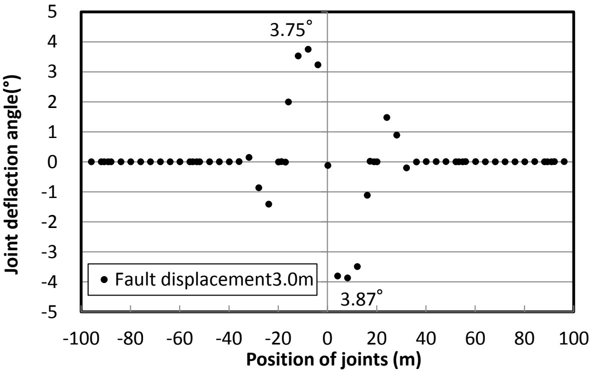


FIG.23 Joint deflection angle

DESIGN FLOW OF LDAPS

To design the pipeline with LDAPS, it is required that the unit should be placed with adequate span in accordance with anticipated fault displacement, fault crossing angle and ground condition. If the designed span is shorter than adequate span, it becomes excessive design. Meanwhile, if it is longer, it may not meet the required value on axial force, joint deflection angle and stress.

In this chapter, we describe the design flow of LDAPS using FEM analysis (Fig.25).

STEP 1 Analyze pipeline with standard length pipes [i) and ii) of Fig.25]

Performance evaluation of pipeline consists of standard length pipe is conducted through FEM analysis. The criteria are as follows;

Axial force: 3DkN and under

Joint deflection angle: limit joint deflection angle and under

Stress generated on pipe body: proof stress (270MPa) and under

STEP 2 Set preliminary span [iii) of Fig.25]

When pipeline with standard length pipes is not under the criteria, the span of unit should be decided so that the unit will be placed where the deflection angle is equal or less than threshold value θt (*2 of Fig.25). The span selected by this method tends to be same as adequate span or more than that.

STEP 3 Decide span [iv), v), vi), vii) of Fig.25]

Axial force, joint deflection angle and stress generated on pipe body are analyzed and evaluated again in a row. When axial force is not under the criteria, new span S1 is decided using the formula (3).

$$S_1 = S_2 \frac{f_1}{f_2} \tag{3}$$

where,

S1	New Span (m)
S2	Span on analysis condition (m)
f1	Axial force from analysis result (kN)
f2	Axial force at criterion value (=3DkN, D:diameter)

When axial force meets criterion value and joint deflection angle and stress do not meet the criteria, it is required that span or each pipe length should be shorter until it fulfills the criteria.

The flow of iv) through vii) of Fig.25 will be repeated until proper span is determined.

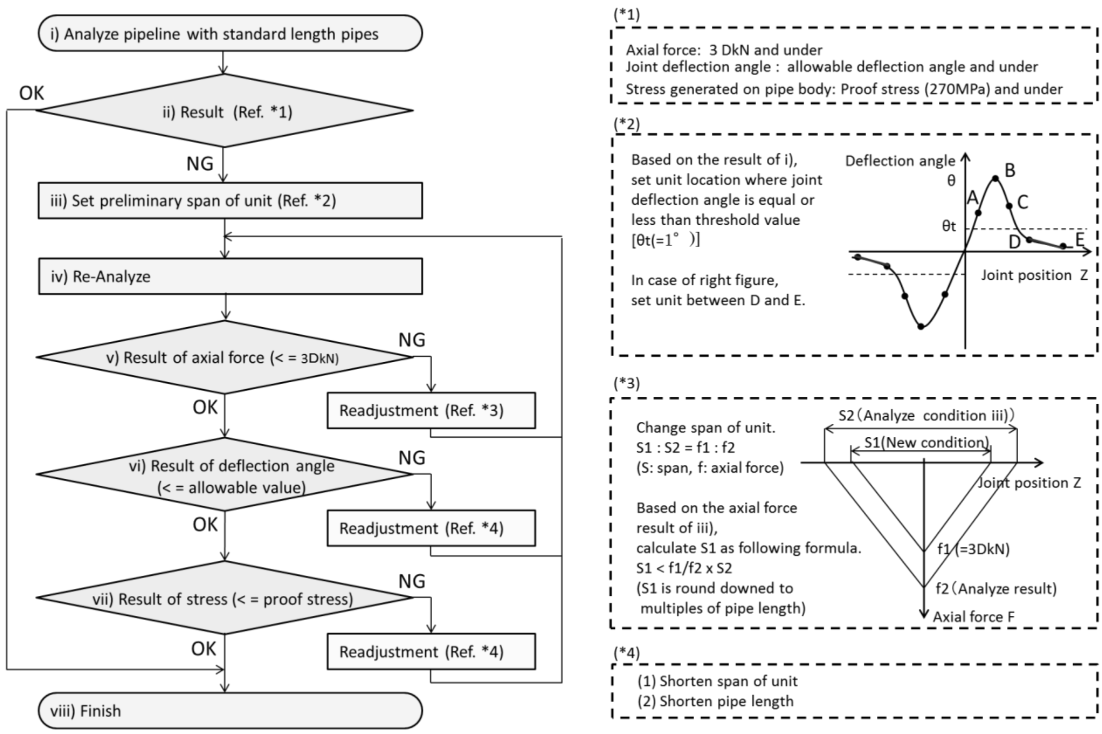


FIG.25 Design flow of LDAPS using FEM analysis

DESIGN METHOD WHEN A LOCATION OF FAULT IS NOT CLEARLY IDENTIFIED

On the above analysis, the location of fault was considered as the center of the span and the units are placed evenly. However, there are cases where the exact locations of fault cannot be identified. To handle this issue, we studied the safety of LDAPS under the situation. Fig.26 shows the analysis condition. We selected seven locations as a possible fault. No.1.3.4.5 and 7 are at joint portion, No.2 is at pipe body, No.6 is at unit. We conducted FEM analysis at each location. Analysis condition is same as that of Table 3 and Fig.19 except the fault movement location.

Fig.27 shows comparison of analysis result. Maximum axial force, maximum joint deflection angle and maximum stress are indicated. No.5 and No.7 showed relatively higher value than others, but still within the criteria. As a result of this analysis, we found all the locations to be safe if the fault cross the pipeline anywhere between the units.

Fig.28 shows an example of design at assumed area of fault. The key is to set a unit outside of assumed area on both side and some units inside the area. The span in the assumed area is S, whereas the span between a unit out of the area and a unit at edge is S'(<S). The S shall meet the criteria through FEM analysis. In case of above mentioned analysis, S will be 36m. Using this design method, "Large displacement absorption units" can be properly set and perform to secure the safety of water pipeline wherever a fault exists in the assumed area.

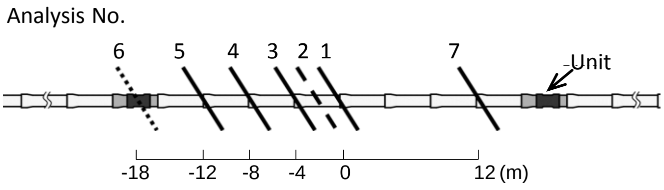


Fig.26 Analysis condition (Slash: Fault)

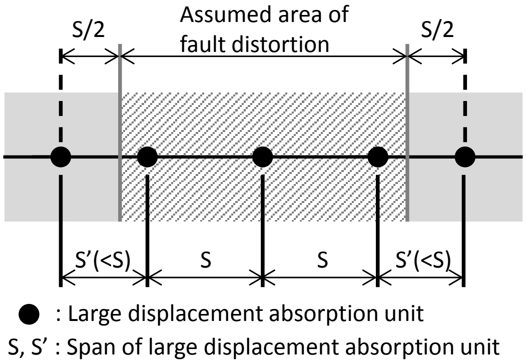


Fig.28 Design for assumed area of fault distribution

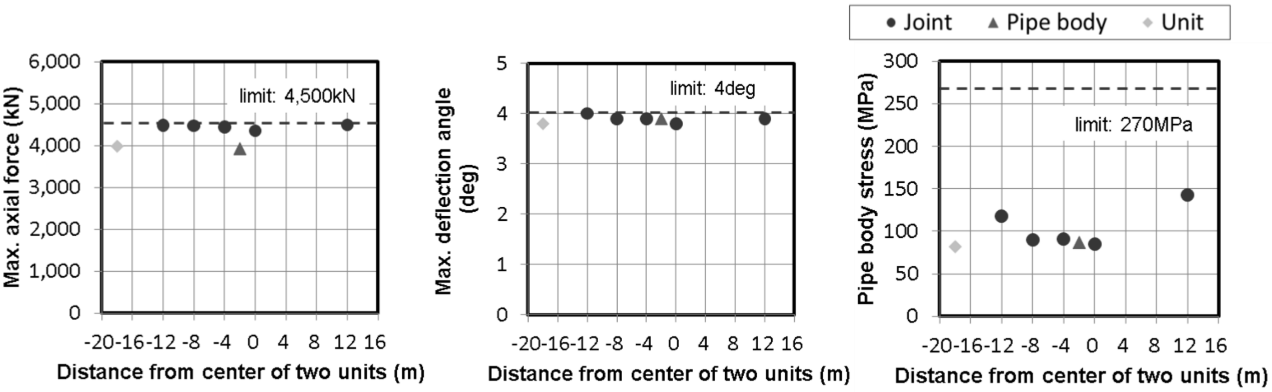


Fig.27 Comparison of analysis results

CONCLUSION

In this study, we focus on larger diameter pipe which cause serious damage to water system by earthquake and conduct FEM analysis to understand how much fault displacement the normal pipeline can absorb. Furthermore, we establish the countermeasure design method against such large fault displacement.

1) DN1500 US-type ERDIP pipeline can absorb 1.6m fault displacement by the joint expansion/contraction and deflection. The stress generated on pipeline by fault displacement is within elastic range.

2) As a countermeasure for 1.6m or more fault displacement, it was found that LDAPS is effective to absorb axial direction local-displacement and can accommodate the 3m or more ground displacement. LDAPS consists of “Large displacement absorption unit” which has 10 times bigger expansion/contraction amount than regular joint and ERDIP pipe.

3) “Large displacement absorption unit” should be placed on the both side of fault at the locations where they are not subjected to deflection of more than 1 degree based.

4) In case that the exact location of fault is not identified, we establish the design method using “Large displacement absorption units”.

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